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NKF-B-SF
WP96-362
24 June 1996

Lake Shore, Inc.
An Oldenburg Group Company
P.O. Box 809
Iron Mountain, MI 49801

Attention: Mr. Rick Shemanski

Subject: Modular Causeway Ferry; Vibration Tests; P.O. No. 113667

Enclosure: (1) NKF Report No. 9703-01/1, "Vibration Measurements on Modular Causeway Ferry (MCF)," dated 21 June 1996 (3 copies)

Gentlemen:

We are enclosing herewith our final report conducted under the subject purchase order.

Please note that the linear vibration measurements (accelerometers) are within acceptable limits with the following exceptions:

<u>**Base of Engine**</u>: The maximum vibration level of 0.40 inch/sec is somewhat higher than desirable. It is recommended that the holddown bolting be checked for adequate torque. It is also recommended that the stiffness of the engine foundation be examined.

<u>**Top of Gearbox**</u>: The measured vibratory velocity is grossly excessive which can lead to premature failures. It is recommended that the feasibility of adding stiffening to the unit be studied.

With regard to the torsional stresses, which are based on the combined results of the measured torsional amplitudes at the front end of engine and the Detroit Diesel mathematical analysis report, we find the following:

- An exceedingly high stress of 107,140 psi was calculated at about 2,150 rpm due to a 3rd Mode, 4th Order vibration. Such level of vibratory stress would result in rapid fatigue failure.

- The four individual components of vibration shown in Table 3 of the report all occur in a close range of 2,000 to 2,200 ERPM. Therefore, these components can be additive, depending upon their relative phase relationships.

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- We have therefore recommended that the mathematical analysis be reevaluated and stresses recalculated, as necessary.

Should you wish to pursue our recommended additional studies, NKF would be pleased to furnish you with a quote. If you have any questions, please call the undersigned at (703) 358-8722 or Mr. Sam Feldman at (703) 358-8633.

Sincerely,

NKF ENGINEERING, INC.

Eric Schulz

Erich Schulz
Manager
Structural Dynamics Department

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LIST OF FIGURES

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1.0 INTRODUCTION

Lake Shore Incorporated (LSI) was the prime contractor to the U.S. Army in the production of the Modular Causeway Ferry (MCF). NKF Engineering, Inc. (NKF) was contracted by LSI under Purchase Order No. 113667 to conduct first article vibration measurements under operational conditions.

Translational and torsional vibration measurements were recorded while underway during trials in Ontonagon, Michigan on Lake Superior. The test was conducted in accordance with the test procedure (Appendix A) and References 1, 2, and 3. This document provides a final report on the survey including: procedure, instrumentation used, calibration method, and a summary of all significant results.

2.0 OBJECTIVES

The objective of this study was to measure and record the vibration characteristics of one MCF propulsion module during full load, full speed sea trials in accordance with References 1, 2, and 3.

3.0 MCF CHARACTERISTICS

General Characteristics: Figure 1 provides a sketch of the MCF which is a modular self-propelled ferry. In the tested configuration, it is 320 feet long x 24 feet wide x 4.5 feet deep. General construction is of ISO compatible steel modules joined by USN standard flexor and shear connectors. Cargo capacity of the MCF in the test configuration is specified as 350 short tons. Maximum speed is specified as 6 knots at full load.

Propulsion modules (40 feet x 8 feet x 4.5 feet) are located aft; one port, one starboard. Propulsion is provided by a Detroit Diesel 8V92TA engine operating through a gearbox to a flush-mounted 360-degree steerable waterjet thruster. A single 4 feet x 6 feet Control Cab (CC) is located on one of the propulsion modules. LSI Drawing No. E26106 provides an outline of the drive train installation.

4.0 TECHNICAL APPROACH

- Determine the longitudinal vibration characteristics of the propulsion system with an accelerometer measuring the longitudinal motion of the waterjet foundation. Vibratory motions of the engine foundation to be measured with an accelerometer mounted in the vertical direction.

- Determine the torsional vibration characteristics of the propulsion system with a rotational velocity transducer, or torsiograph mounted to the free end of the engine. Dynamic angular displacements at the free end of the engine will be used along with the torsional analysis (Reference 4) to determine maximum dynamic stresses and torque across the gears.

- Measure hull vibrations at the stern of the propulsion module in three principle axes. Vibratory motions will be recorded in acceleration units during trials and converted to velocity or displacement units as necessary. Vibratory motions in the CC in the principle direction of motion will also be measured. Additionally, vibration at any location observed to be excessive or potentially damaging will be measured.

5.0 PROCEDURE

5.1 INSTALLATION PROCEDURE

An adapter shaft to attach the torsiograph to the free end of the propulsion engine crankshaft was provided by LSI. The adapter was designed to interface between the free end of the engine at the crankshaft and the rotational velocity transducer (torsiograph).

Twelve-volt DC power from the propulsion module batteries was used to power the amplifiers and recorder.

The test equipment installed consisted of sensors, signal cable, signal conditioners, calibration equipment, and a recording device. The table below lists the data acquisition system used to complete the test.

QTY	DESCRIPTION	MANUFACTURER	MODEL NO.
6	Accelerometer	Wilcoxon Research	766
2	Accelerometer	PCB Piezotronics	327 A01
1	Rotational Velocity Transducer (Torsiograph)	Knopfle-Stein	s/n 11
1	Variable Reluctance Pickup (Event Marker)	Electro Corporation	3030AN606909
1	12-Channel Amplifier	PCB Piezotronics	483B07
1	21-Channel FM Tape Recorder	TEAC	XR-7000
1	2-Channel Spectrum Analyzer	Ono Sokki	CF-350
1	Accelerometer Calibrator	B&K	4291

Sensors were installed in the locations/orientations shown in Table 1. The orientation of the accelerometer in the control cab was determined by comparison measurements while operating near full power. The location chosen for the extra accelerometer was the top of the water pump because of low frequency displacements noted at this location during operating conditions. An additional accelerometer was mounted on the top of the spicer gearbox in the athwartship direction. Locations of transducers are shown in Figure 2.

Table 1. Instruments on Starboard Propulsion Unit

ITEM NO.	QTY REQUIRED	EQUIPMENT DESCRIPTION	LOCATION	MEASUREMENT DIRECTION
1	1	Accelerometer	Waterjet foundation	Fore/Aft
2	1	Accelerometer	Diesel engine foundation	Vertical
3	3	Accelerometer	Stern of propulsion module	Fore/Aft, Athwartship, Vertical
4	1	Accelerometer	Control cab	Athwartship
5	1	Torsiograph	Free end of diesel engine	Torsional
6	1	Event Marker	Adjacent to main shaft	Shaft Revolutions
7	1	Accelerometer	Top of water pump	Athwartship
8	1	Accelerometer	Top of Z-drive gearbox	Athwartship

The accelerometer mounting blocks were installed using quick set epoxy, taking care to ensure that the threaded holes and/or studs were in the proper orientation for gage attachment.

The torsiograph was attached to the adapter located on the free end of the starboard propulsion engine at the crankshaft centerline.

The event marker target was installed on the propulsion shaft near the z-drive/water pump shaft using strapping tape.

Signal cables were attached to all transducers and connected to an amplifier/power supply, where necessary, and then directly to the tape recorder. Separate cables were used to monitor the tape recorder outputs with a two-channel oscilloscope.

5.2 TEST PROCEDURE

The approved test procedure is included in Appendix A. The test included recording several minutes of data at constant RPM in approximately 75 RPM increments from idle to full speed. In addition, a sweep was recorded in which the RPM was slowly increased over the full operating range.

The logsheets showing equipment gains and settings are also presented in Appendix A. An instrumentation block diagram for data recording is shown in Figure 3.

6.0 CALIBRATION

6.1 LABORATORY CALIBRATION

The accelerometers and accelerometer calibrator were calibrated at an independent laboratory within 6 months prior to the test. These calibrations demonstrated accuracies to within acceptable tolerances, traceable to the National Institute of Standards and Technology (NIST). The torsiograph was calibrated at NKF's laboratory within 6 months prior to the test. Calibration data and certifications are included in Appendix B.

6.2 FIELD CALIBRATION

A circuit check and physical calibration of the accelerometers were conducted using the accelerometer calibrator to subject the accelerometer to a 1.0 gravity RMS sine motion at a frequency of 80 Hz. The accelerometer output signal passed through all cabling and amplifiers used during the test. The amplifier output was recorded on tape for about 30 seconds. A block diagram of the calibration configuration is shown in Figure 4.

7.0 DATA REDUCTION

The instrumentation used to perform the data reduction/analysis consisted of the following:

QTY	MANUFACTURER	MODEL	DESCRIPTION
1	TEAC	XR-7000	FM Tape Recorder
1	Hewlett-Packard	3566/67A	Spectrum Analyzer
1	Generic	486DX66	Personal Computer (PC)

During data reduction, the conversion from volts to engineering units was calculated using the measured field calibration data from the transducers, signal conditioning gain settings, and recording equipment sensitivity settings.

Using these conversion constants, the constant speed operational data recorded on the tape was then digitized and stored as averaged frequency data by the spectrum analyzer. A flat-top antileakage window was used, and approximately 2 minutes of data was averaged for each constant speed condition. The frequency domain data was acquired and stored in both 50 Hz and 400 Hz full-scale ranges. In the 50 Hz data, frequency resolution was 0.25 Hz. Frequency resolution was 1.0 Hz in the 400 Hz data. These spectra were then transferred to the PC which generated vibratory "waterfall" plots. The data was plotted in velocity units, where the velocity spectra were obtained by frequency domain integration. The torsiograph data was similarly processed and presented in units of degrees (angular displacement).

For the data recorded during the speed sweeps, waterfall-type plots were generated automatically by the spectrum analyzer. The spectra in the sweep waterfalls are instantaneous spectra (from a single time record) and are presented at much closer and uniformly spaced RPM increments than the constant speed runs. These spectra were plotted in units of velocity with the exception of the torsiograph, which was plotted in degrees.

8.0 RESULTS

Appendix C provides "waterfall" analyses for all locations based on the accelerometer measurements at steady speed runs. Table 2 provides a summary of the maximum velocity amplitude extracted from the "waterfall" diagrams

Table 2. Maximum Velocity Amplitudes

LOCATION	DIRECTION	MAXIMUM VELOCITY (MILS/SEC)				
		FREQ.	ERPM	ENGINE ORDER	PEAK AMPL.	RESONANT OR NONRESONANT
Base of Thruster	Fore/Aft	12.5	1,950	1st Thruster	16	Resonant
		43.0	2,200	1st	14	Nonresonant
		95.0	1,950	3rd	65	Resonant
Base of Engine	Vertical	13.0	2,150	1st Thruster	22	Resonant
		22.0	1,325	1st	180	Sharp Resonant
		42.0	2,200	1st	130	Nonresonant
		145.0	2,150	4th	400	Resonant
Hull Stern	Fore/Aft	13.0	2,075	1st Thruster	16	Resonant
		22.0	1,325	1st	12	Resonant
		41.0	2,200	1st	16	Resonant
		125.0	1,900	4th	20	Resonant
Hull Stern	Athw	12.0	1,950	1st Thruster	11	Resonant
		39.0	2,075	1st	48	Resonant
		32.0	1,700	1st	31	Resonant
		95.0	2,000	3rd	55	Resonant
Hull Stern	Vertical	12.5	1,925	1st Thruster	20	Resonant
		39.0	2,075	1st	65	Resonant
		130.0	2,000	4th	46	Resonant
		140.0	2,150	4th	45	Resonant
Control Cab-Lower Aft Port Corner	Athw	13.0	1,950	1st Thruster	15	Resonant
		41.0	2,150	1st	55	Resonant
		55.0	875	4th	140	Resonant
		105.0	2,000	3rd	70	Resonant
Top Water Pump	Athw	41.0	2,150	1st	280	Resonant
Top Gearbox	Athw	41.0	2,150	1st	3,300	Resonant

Appendix D provides similar "waterfall" analyses for the torsiograph measurements. Table 3 provides a summary of the maximum angular displacements measured by the torsiograph, and the calculated torsional stresses based on the stress per degree values from Reference 4.

Table 3. Maximum Torsional Amplitudes Measured at Front End of Engine

ERPM	FREQUENCY (HZ)	MODE	ORDER	AMPLITUDE* (±DEGREES)	CALC (STRESS/DEG.)	STRESS (PSI)	SECTION OF MAX. STRESS
2,000	13	1	1st Thruster	2.0	2,179	4,358	Coupling to Tr. Gears
2,150	145	3	4th Engine	0.11	0.974E6	107,140	Reduction Gear to 1st Shaft
2,200	147	3	4th Engine	0.091	0.199E5	1,811	Crank Throw No. 4
2,200	183	4	5th Engine	0.120	0.199E5	2,388	Crank Throw No. 4

* Amplitude corrected for analysis ratio of B_4/B_1 for each mode

8.1 DISCUSSION OF RESULTS

Linear Vibrations

Based on the analysis of data in Appendix C and Table 2, the vibration velocity amplitudes are well within limits of acceptability, except for two locations. These two are:

- Base of Engine - Vertical @ 2,150 rpm, vel = 0.40 inch/sec
- Top Gearbox - Athwartship @ 2,150 rpm, vel = 3.30 inch/sec

Although References 2 and 3 were identified as requirements for vibration testing, these references do not identify the limits for vibration severity amplitudes. Therefore, we are suggesting the use of Reference 5 as a guide for acceptability of vibration severity.

Reference 5 is currently being considered by the SNAME HS-7 Committee and the International Standards Organization (ISO) as a recommended guide for shipboard vibration. In general, a velocity level of about 0.3 inch/sec peak is tolerable. Levels higher than this should be investigated.

Thus, based on the summary of measured data (Table 2), it is apparent that vertical vibration at the base of engine is somewhat high, and the athwartship vibration at the top of gearbox is excessively high.

Torsional Vibrations

Table 3 provides the torsional stresses calculated for the 1st, 3rd, and 4th mode maximum torsional amplitudes measured during the test. These stresses are based on the analysis presented by Reference 4 in combination with the measured torsional vibration amplitudes presented herein.

The 13 Hz component agrees with the calculated first mode natural frequency (Reference 4) and is excited by the 1st order of the thruster or misalignment of the universal joint shafts.

The most significant stress of 107,140 psi between Mass 12 and Mass 13 is associated with a 3rd Mode, 4th order vibration at 2,150 ERPM. This value is questionable because of the excessively high value. A quick check of the calculated stress per degree values indicate significant differences between NKF calculations and those provided by Reference 4.

The stresses calculated for the 1st and 4th mode measured amplitudes would be considered acceptable when taken individually. However, since these components all occur in the 2,000 to 2,200 ERPM range, they will periodically be additive and subtractive, depending on their phase relationships. Therefore, it is possible that the torsional vibration stresses at 2,150 ERPM may exceed the MIL-STD-167 limits, even without the questionable stress of the 3rd Mode, 4th order.

9.0 CONCLUSIONS AND RECOMMENDATIONS

9.1 LINEAR VIBRATION

The velocity levels at all stations measured are considered acceptable with the following exceptions:

- **Base of Engine**: The maximum vibration level of 0.40 inch/sec is somewhat higher than desirable. It is recommended that the bolting be checked for adequate holddown torque, and inspections be conducted periodically.

- **Top Gearbox:** The maximum vibration level of 3.30 inch/sec is grossly excessive, indicating the need for corrective action. Suitable stiffening in the athwartship direction may alleviate this problem.

9.2 TORSIONAL VIBRATION

The most serious vibration is the component measured at 2,150 ERPM associated with the 3rd Mode, 4th order. A calculated stress of 107,140 psi would result in rapid fatigue failure. Therefore, we believe the calculated stress per degree provided by Reference 4 is open to question. It is recommended that this be reexamined.

An alternative to this approach would be to measure the torsional stress with strain gages at the shaft section in question.

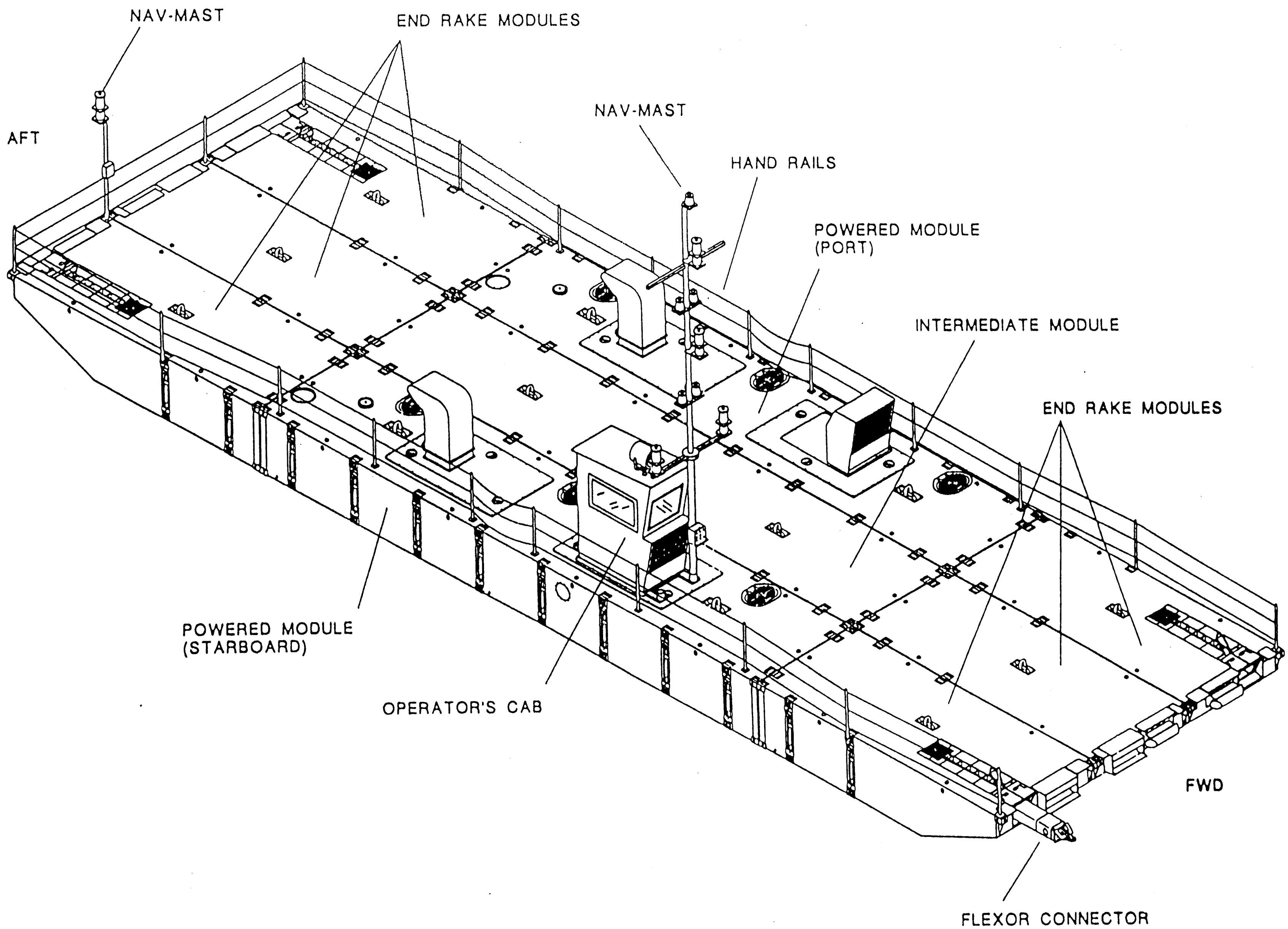

Figure 1. Outline of Modular Causeway Ferry

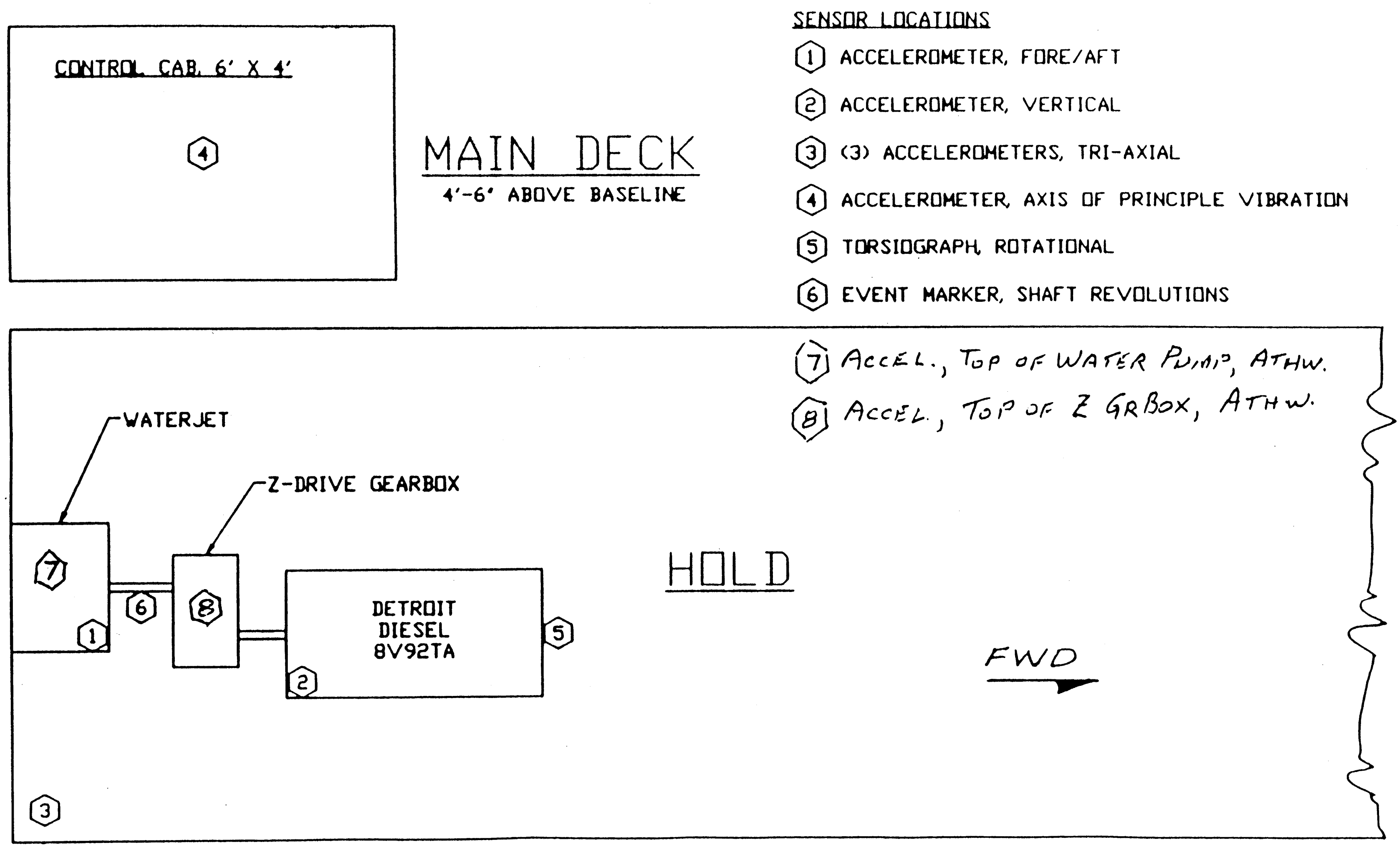

Figure 2. Vibration Sensor Locations

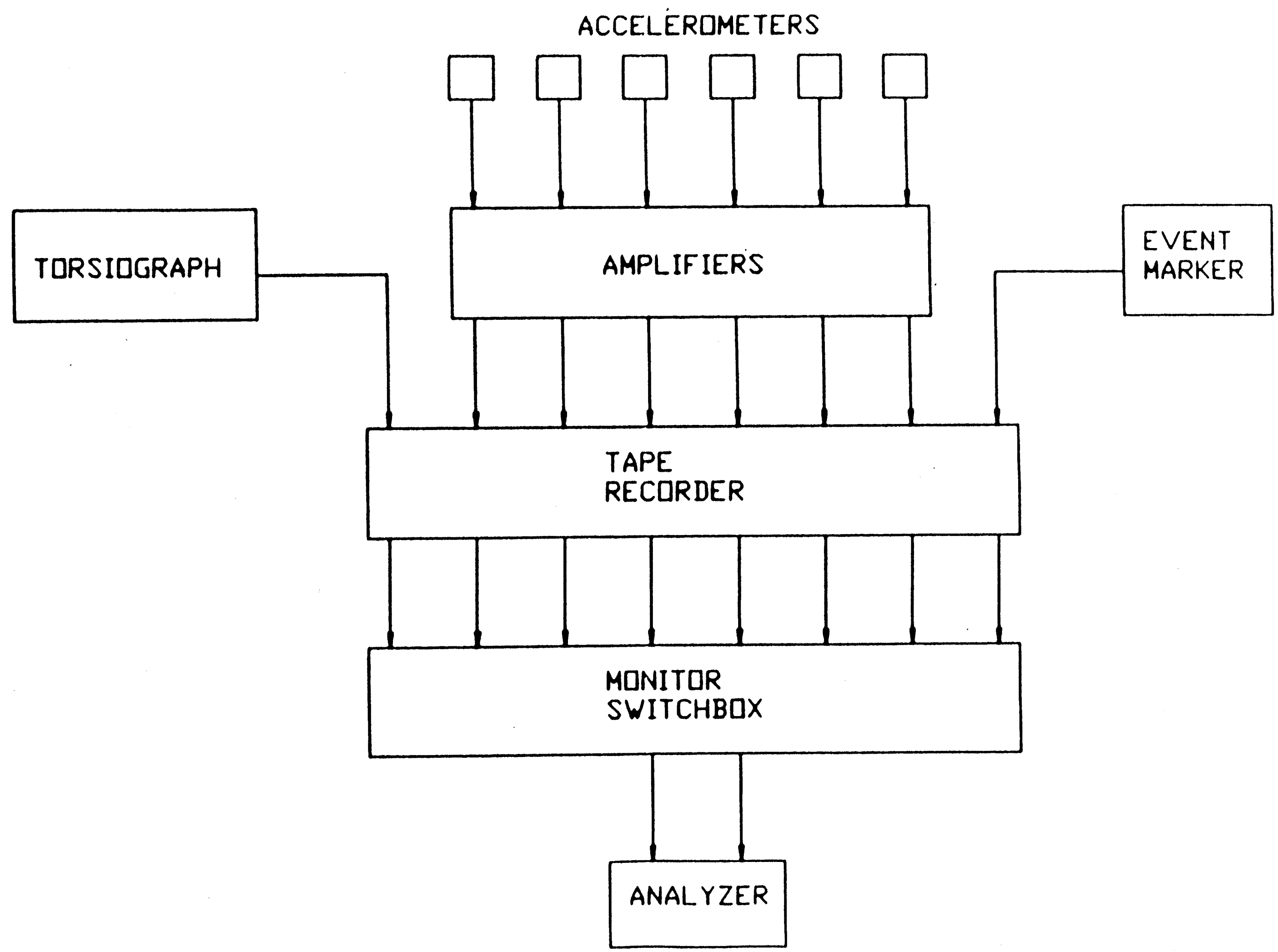

Figure 3. Instrumentation Block Diagram for Data Recording Mode

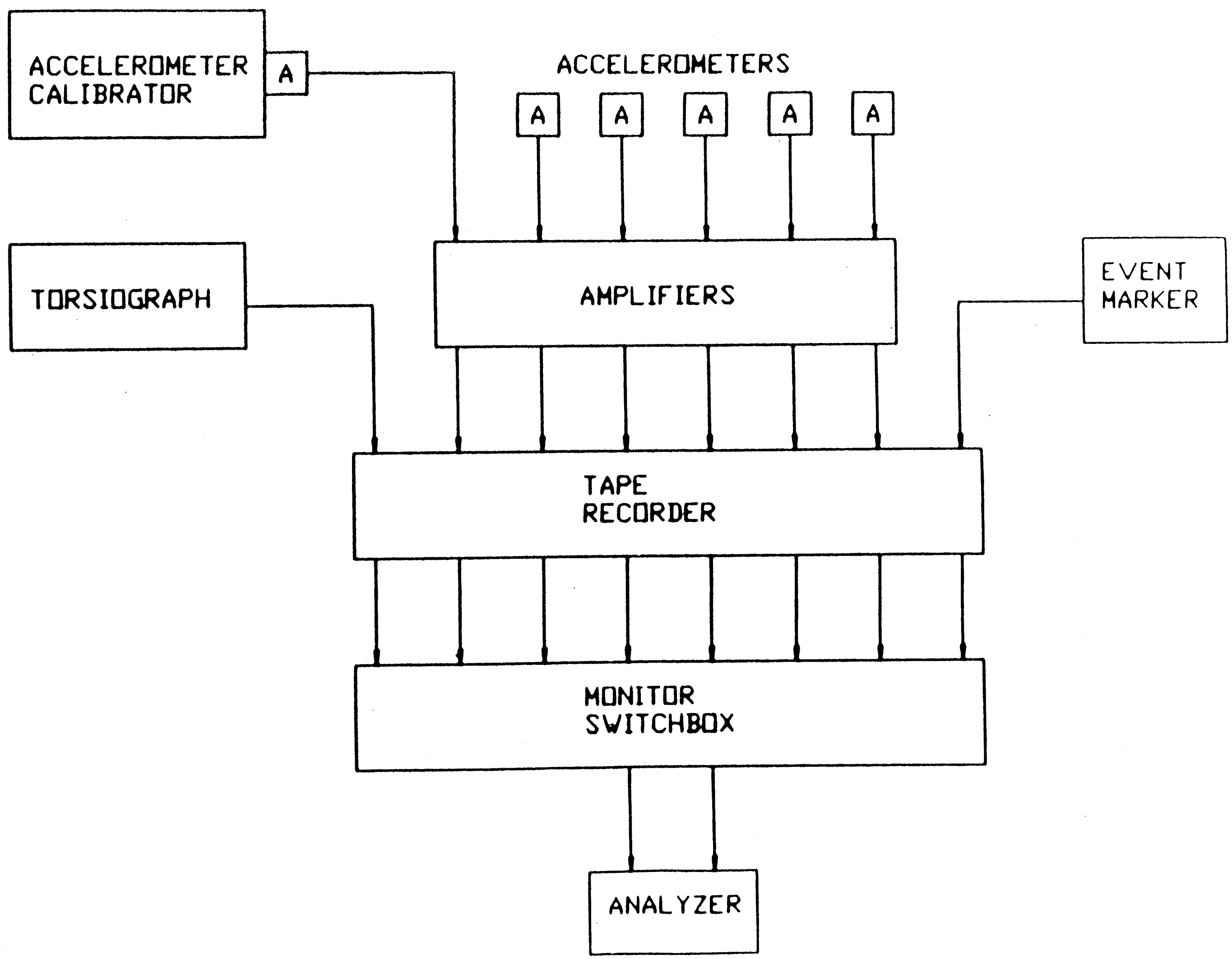

Figure 4. Instrumentation Block Diagram for Accelerometer Calibration Mode

10.0 REFERENCES

1. MIL-STD-167-2, "Mechanical Vibrations of Shipboard Equipment (Reciprocating Machinery and Propulsion System and Shafting), Types III, IV, and V," dated 1 May 1974.

2. SNAME Technical & Research Code C-1, "Code for Shipboard Vibration Measurement," dated January 1975.

3. SNAME Technical & Research Code C-4, "Local Shipboard Structures and Machinery Vibration Measurements," dated December 1976.

4. Detroit Diesel Corporation Engineering Analytical Report I3R-011-11776-00, "Torsional Vibration Analysis of an 8V-92TA Engine Driving a Waterjet Propulsion Thruster through a Twin Disc MG 5111 (1.74:1) Marine Gear with LS 14E-3701 Coupling."

5. International Standard ISO 6954 (1995 proposed).